68-FM-203

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

MSC INTERNAL NOTE NO. 68-FM-203

August 12, 1968

COMPATIBILITY OF LM PGNCS AND AGS CONCENTRIC RENDEZVOUS MANEUVER COMPUTATIONS

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(This revision supersedes MSC Internal Note No. 68-FM-95 dated April 17, 1968)

MISSION PLANNING AND ANALYSIS DIVISION

MANNED SPACECRAFT CENTER
HOUSTON, TEXAS

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PROJECT APOLLO

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SUMMARY

This report presents a summary of PGNCS and AGS capabilities to perform targeting and guidance computations for the rendezvous phase of the lunar landing mission. Differences in PGNCS and AGS computations are discussed, and the targeting and guidance equations of each are compared.

Analysis of data generated from engineering simulations of the programs implies that the only program differences of major significance are

1. Coasting integrator differences.

2. V_G extrapolation in the PGNCS.

3. Different engine cutoff criteria.

4. The lack of an option in the PGNCS to allow an astronaut input request for the positioning of CDH at a multiple of 180° from CSI. No program changes are recommended in this report other than to change the PGNCS CSI iteration logic to allow the astronaut to request a positioning of CDH at a multiple of 180° from CSI.

INTRODUCTION

The maneuvers of the rendezvous phase of the lunar landing mission which the primary guidance and navigation control system (PGNCS) and abort guidance system (AGS) of the LM must guide are

1. CSI - coelliptic sequence initiation.

2. CDH - coelliptic maneuver.

3. TPI - terminal phase initiation.

4. MCC - midcourse corrections.

This report describes both the primary onboard guidance equations, i.e., those in the PGNCS, and the abort guidance equations, i.e., those in the AGS. The PGNCS description is based on references 1 and 2. The AGS description is based on references 3 through 6. Table I lists the differences in computational constraints and in the techniques employed in the two systems.

PGNCS RENDEZVOUS PHASE COMPUTATIONS

Rendezvous Targeting

The PGNCS uses two methods of state vector propagation during a coast: (1) the Keplerian (two-body) method, and (2) precision integration using Encke's method. The precision coasting integrator uses a potential function based on the perturbation terms J_2, J_3, and J_4 for the earth and J_2 and J_{22} for the moon.

There are four main areas to the PGNCS rendezvous phase computations: (1) pre-CSI, (2) pre-CDH, (3) pre-TPI, and (4) midcourse corrections. Each area will be discussed separately. The astronaut has the option to overwrite the components of any maneuver. Normally this option will be used to null out-of-planeness of the LM orbit to the CSM orbit. Table II summarizes the rendezvous targeting program tolerances.

Pre-CSI.- The pre-CSI targeting program computes a horizontal velocity increment at a specified time which, along with the CDH coelliptic maneuver, will cause the active vehicle to arrive with the desired line of sight at the TPI time. The program accepts the following inputs:

1. Choice of active vehicle.

2. Number of apsidal crossings after CSI at which CDH occurs.

3. Time of CSI.

4. Desired elevation angle at TPI.

5. Time of TPI.

The desired elevation angle may be input from 0° to 360°, and may result in either rendezvous from below or from above. First quadrant and third quadrant angles are equivalent inputs. Second quadrant and fourth quadrant angles are equivalent inputs. If the desired elevation angle is in the first quadrant, the relative positions of the vehicles at TPI will be either active vehicle below and behind the passive vehicle or above and ahead. When the desired elevation angle is in the second quadrant and relative vehicular positioning at TPI will be either active vehicle below and ahead or above and behind.

The program begins computations by updating the vehicle's state vectors to the time of CSI with the precision integrator. The active vehicle state vector at CSI is rotated into the orbital plane of the passive vehicle. The passive vehicle state vector is then advanced with two-body motion to the time of TPI, and the state vector at this time is stored.

The first guess at ΔV_{CSI} is obtained by subtracting the active vehicle's horizontal velocity at CSI from the horizontal velocity required to obtain at 180° from CSI a radius magnitude equal to that of the passive vehicle at TPI. The ΔV_{CSI} guess is then added to the state vector and the time to the periapsis is solved for with two-body equations. If the resultant orbital eccentricity is less than .0001 or if altitude rate, $|\dot{R}|$, is less than 0.05 fps, the time to the periapsis is not computed, and the CSI point is considered to be an apsis. The time of the CDH maneuver is computed as a function of the time to periapsis, the orbital period, and the desired apsidal crossing.

Both state vectors are advanced by the Keplerian mode from CSI to CDH time. The phase angle at CDH is computed and the passive vehicle's state vector propagated by the Keplerian method through the phase angle to phase match with the active vehicle's state. The coelliptic Δh is the target radius minus the chaser radius. The coelliptic maneuver ΔV is calculated and added to the active vehicle's state vector.

The active vehicle is advanced to TPI time with the Keplerian integrator. Then the phase angle error, $\delta\gamma$, is obtained as the difference of the phase angle at TPI and the desired phase angle. The desired phase angle is a function of the input desired elevation angle and the coelliptic Δh.

An iteration on ΔV_{CSI} is done to drive $\delta\gamma$ to zero. The first increment to ΔV_{CSI} is $\Delta V = -10$ fps. Subsequent iterations on ΔV_{CSI} are linearizations of ΔV guesses and resultant phase angle errors at TPI. The iteration is terminated whenever $\Delta V < 0.1$ fps.

If any of the following conditions are encountered during program calculations, the iteration sequence is terminated:

1. If on the first iteration the active vehicle goes **above** the passive vehicle and if the desired line-of-sight vector does not intersect the passive vehicle's orbit.

2. If two succeeding iterations result in ΔV's for CSI greater than 1000 fps.

3. If the iteration counter exceeds 15.

4. If predicted CDH time is greater than desired TPI time.

After a CSI iteration has converged, the program checks the following constraints:

1. Periapsis altitude after both the CSI and CDH maneuvers should be greater than 85 n. mi. for the earth and 35 000 ft for the moon.

2. The time between the maneuvers should be greater than 10 minutes.

If one of the above six constraints is violated, an entirely new iteration sequence is initiated. An attempt is made to drive $\delta\gamma$ to zero by changing the catch-up direction. This is done by incrementing the original ΔV_{CSI} oppositely to the first iteration sequence in steps of 50 fps. That is, if the first iteration sequence attempted to drive $\delta\gamma$ to zero by incrementing (decrementing) the initial ΔV_{CSI} guess, then the new sequence will decrement (increment) the initial ΔV_{CSI}. Whenever $\delta\gamma$ changes sign as a result of one of the 50-fps steps, then a linear iteration is set up. If the second iteration sequence also fails one of the constraints, the program is exited with the alarm code referring to the failure of the first iteration sequence.

Pre-CDH.- The pre-CDH targeting program in the PGNCS has the following inputs:

1. Choice of active vehicle.

2. Time of the CDH maneuver.

3. Desired elevation angle at TPI.

The program advances the state vectors to CDH time with the precision integrator. Then the active vehicle's state vector is rotated into the orbital plane of the passive vehicle. The CDH maneuver is computed as in the pre-CSI program and added to the active vehicle's state. Then both vehicles' state vectors are advanced with the Encke integrator to the time of TPI and the pre-TPI program is called to do an iteration on the elevation angle desired at TPI. If the iteration can find no time corresponding to the desired elevation angle, the program is exited with a failure indicator displayed to the astronaut. The astronaut may then recycle the program by changing the input values.

Pre-TPI.- The pre-TPI program requires the following inputs:

1. Choice of active vehicle.

2. Time of the TPI maneuver.

3. Travel angle, ωt, of the passive vehicle during the transfer phase of the active vehicle.

4. Desired elevation angle.

The elevation angle desired must be defined from 0° to 360°. If the desired elevation angle is input as zero, then no iteration is done, but the actual line-of-sight angle is computed and displayed.

Both state vectors are moved to the time of TPI with the Encke integrator. The actual and desired phase angles are computed and an iteration is done on the TPI time by

$$\Delta t = \frac{\text{error in phase angle}}{\text{difference in orbital rates}}$$

The state vectors are advanced through each Δt correction with Keplerian motion. The phase angle iteration tolerance used is 0.1°.

The desired intercept time is computed with two-body equations as a function of TPI time and the true anomaly difference, ωt. The precision integrator is used to advance the state vector of the passive vehicle to the time of intercept, and the resulting position vector is the true target point.

The pre-TPI targeting routine computes a TPF aim point for the Lambert guidance. Since the Lambert guidance equations solve the intercept problem with two-body motion, the targeted aim point must be biased from the true TPF target so that the actual resultant trajectory intercepts the true target. The bias is calculated as follows: The pre-TPI program utilizes a Lambert routine (with Keplerian equations) to solve for the velocity required at TPI to result in an intercept of the true target at TPF. The precision integrator propagates the resulting state vector to TPF time. The chaser position vector so obtained at TPF time will miss the true target. The miss is due to the lack of perturbations in the potential function model used in the Lambert routine. Therefore, a new aim point is generated by biasing the true target by the miss vector. Then the pre-TPI program uses the Lambert routine to solve for the velocity required at TPI to intercept the biased TPF aim point. Another miss vector is obtained with the precision integrator and the final aim point is determined by biasing the last aim point by the new miss vector. This final aim point, biased from the true target, is the targeting passed to the Lambert guidance program.

If any of the following conditions occur during pre-TPI computations, the program is exited and an alarm displayed:

1. The iteration counter exceeds 15 iterations.

2. The desired line of sight from the active vehicle does not intersect the circular orbit with radius equal to that of the passive vehicle at TPI.

3. The input desired elevation angle is not compatible with a feasible rendezvous; i.e., desired elevation angle is greater than 180° but the chaser is below the target, or desired elevation angle is less than 180° but the chaser is above the target.

The rendezvous midcourse program accepts as input the choice of active vehicle.

The time of the maneuver is taken to be present time plus a delay time. The delay time is the time required for the astronaut to prepare for a maneuver. The delay times used will be in erasable memory and will be determined nominally as a function of crew training prior to each flight. There will be two different delay times in the program: one for LM active, and the other for CSM active. The maneuver targeting is computed as in the pre-TPI program.

Guidance

The PGNCS utilizes a fixed inertial guidance scheme for the CSI and CDH maneuvers. This guidance scheme is denoted as external ΔV, EXDV. The pre-CSI and pre-CDH programs generate targets for EXDV. The pre-CSI and pre-CDH ΔV targets are computed parallel to the orbital plane of the passive vehicle. The targeted out-of-plane component is zero. Then the external ΔV guidance sets up an active vehicle, local horizontal coordinate system at the time of main engine ignition. The maneuver targeted parallel to the passive vehicle's plane is burned out in the active vehicle's plane; i.e., no out-of-plane ΔV results. The external ΔV targets may also be generated in the RTCC and uplinked to the LGC. External ΔV guidance accepts the following as inputs:

1. Main engine ignition time, T_{IG}.

2. The target ΔV vector in a local horizontal coordinate system defined at T_{IG}.

3. Thruster to be used.

The guidance equations are used to compute an estimate of the required thrusting time. The computation of burn time is based upon the assumption that the acceleration level remains constant through the burn. The estimated acceleration level is computed as a function of a prestored thrust level for the thruster selected and the current estimate of the vehicle's weight. The burn-time computation has two sources of error since the acceleration is not constant through the burn and since the stored thrust level may not agree with the actual. From the burn-time estimate the equations compute the resultant burn arc. The inertial thrust direction is determined by biasing the in-plane component of the input target ΔV vector by one-half the estimated burn arc. The maneuver is performed by thrusting along the inertial direction. Engine cutoff is controlled by the burn time remaining, T_{GO}, which is computed as a function of the velocity to be gained, V_G. The T_{GO} calculations include tail-off considerations. The T_{GO} parameter is recomputed each 2-second guidance cycle; however, it is not redetermined after it becomes less than 4 seconds. When T_{GO} becomes less than 4 seconds, the engine cutoff timer is set to shut down the engine T_{GO} seconds later. T_{GO} is not used for a manually controlled RCS burn.

Lambert steering is the guidance method used to perform the TPI and midcourse maneuvers. The pre-TPI and midcourse targeting programs supply the inputs needed for Lambert guidance:

1. Main engine ignition time.

2. Time of intercept, TPF.

3. Aim point vector at TPF.

4. Thruster to be used.

The velocity required, $\overline{V}_R$, is calculated by passing a Lambert solution between the current vehicle position vector and the aim point vector. The velocity to be gained, $\overline{V}_G$, is computed as the difference between the required velocity, $\overline{V}_R$, and the current vehicle velocity. The LM thrusts along the $\overline{V}_G$

vector. The PGNCS accounts for engine gimbaling in the DPS, and engine cant in the APS, and attempts to align the actual thrust vector along the desired thrust direction. The T_{GO} parameter is computed as in EXDV. If a PGNCS guided maneuver is estimated to be less than 6 seconds long, no actual steering is performed. When T_{GO} becomes less than 4 seconds, the vehicle is put in the attitude hold mode and the thruster is shut off T_{GO} seconds later. The calculation of $\overline{V}_R(t)$ and subsequently $\overline{V}_G(t)$ does not occur instantaneously on request from the guidance logic; the computing time varies as a function of the number of higher priority requests to which the computer is responding. The computer always gives navigation and steering functions priority over computation of a new Lambert solution. At the beginning of each guidance cycle the program determines whether the new $\overline{V}_G$ has been calculated; if it has, the new $\overline{V}_G$ is extrapolated to the time of the current guidance cycle and a new request for a Lambert solution is made. If a new $\overline{V}_G$ is not available, the $\overline{V}_G$ used on the previous guidance cycle is extrapolated to the time of the current guidance cycle. Since $\overline{V}_G(t)$ becomes available after the time t, it is first used on the first guidance cycle following completion of its calculation. To obtain $\overline{V}_G(t+\Delta t)$ for use in the steering program, $\overline{V}_G(t)$ is extrapolated to $t + \Delta t$ by the equation:

$$\overline{V}_G(t+\Delta t) = \overline{V}_G(t) + (\overline{b})(\Delta t) - \overline{\Delta V}$$

The vector $\overline{\Delta V}$ is the sensed incremental velocity during the interval Δt. The vector $\overline{b}$ is an approximation of the time derivative of $\overline{V}_G$. The approximation of $\overline{b}$ is computed utilizing values of time dependent variables, such as the gravity vector, which are determined at time t. The assumption that $\overline{b}$ is a constant over the interval Δt results in an extrapolated $\overline{V}_G(t+\Delta t)$ which is incorrect. A new $\overline{b}$ vector is calculated only whenever a new $\overline{V}_G$ is determined from the Lambert equations. Due to computational priorities, it is not uncommon for the steering to compute T_{GO} based on a $\overline{V}_G$ extrapolated over 6 seconds. Errors in the burn occur when such an extrapolated $\overline{V}_G$ is used to calculate the final T_{GO}. When a final T_{GO} is near the 4-second control value and has been determined with a $\overline{V}_G$ extrapolated over several guidance cycles, then resultant $\overline{V}_G$ residuals can be significant.

AGS RENDEZVOUS PHASE COMPUTATIONS

The AGS computations use two-body equations. The targeting and guidance philosophy differs from the PGNCS in that the CSI and CDH maneuvers are resolved each 2-second guidance cycle. The result of the AGS CSI-CDH guidance is that the thrust direction is not inertially fixed as in the PGNCS.

The AGS routine which computes CSI targeting may be called up by the pilot prior to the time of CSI; however, subsequent iterations of the equations occur at 2-second intervals. Nominally, the CSI routine will be activated long enough before CSI time for a convergent solution to be generated before ignition time. The CSI routine expects these inputs:

1. Time of CSI.

2. Time of TPI.

3. Desired elevation angle at TPI.

4. Apsidal crossing desired for CDH.

5. An indicator defining CDH to be at an apsidal crossing or to be a multiple of 180° from CSI (circular mode).

The CDH maneuver may be specified to occur at the first, second, or third apsidal crossing after CSI. An option exists which allows the astronaut to define CDH to be a multiple of 180° from CSI. The central angle so defined must be no greater than 540°. Operational procedures state that the circular mode will be used by the crew whenever the CSI altitude rate $|\dot{R}| < 10$ fps.

The CSI routine makes its first three iterations of the equations with prestored values for ΔV_{CSI} (-40 fps, 0 fps, 40 fps). An iteration procedure is then started which minimizes the cost function, which is the absolute value of the phase angle error at TPI. Each particular trial increment to the LM horizontal velocity at CSI is added to the LM state vector parallel to the CSM plane. Both the LM and CSM state vectors are advanced to the time of CDH by a Keplerian ellipse predictor.

The CDH routine accepts as its only input the time-to-go to CDH. The routine computes the velocity increment with horizontal component parallel to the CSM orbital plane necessary to give the LM an orbit coelliptic to that of the CSM. The CDH velocity increment is added to the LM state. Both vehicles are assumed to have near circular orbits after CDH, and the true anomaly predictions for TPI time are computed accordingly. That is, to compute the phase angle at TPI the only parameters needed are the true anomalies of both vehicles at desired TPI time. The true anomaly of each vehicle at TPI is approximated by

$$\Theta = \eta \cdot \Delta T + c \dot{R} ,$$

where ΔT is the time from CDH to TPI, η is the mean orbital motion, $\dot{R}$ is the radial rate after CDH, and c is a prestored constant defined in reference 6. The cost function is then calculated as the absolute value of the difference in the approximated phase angle at TPI and the desired phase angle at TPI. Accuracy of the cost function computation degrades significantly for orbital eccentricities greater than 0.015 and coelliptic height differences greater than 600 000 ft. The iteration on ΔV_{CSI} required to minimize the cost function will continue until the change to ΔV_{CSI} computed is less than 0.15 fps.

The AGS makes no checks on unsafe periapsis, unreasonable ΔV costs, or unrealistic times between maneuvers. Furthermore, the predicted periapsis height after the CSI maneuver is not available to the astronaut through the Data Entry and Display Assembly (DEDA) readouts until after CSI execution. DEDA is a general purpose input-output device linking the astronaut with the AGS computer.

The AGS has two TPI options. One route computes the TPI maneuver at a fixed time. The only other input needed is the time of transfer. This option will ordinarily be used only during maneuver execution. The other TPI option is called the TPI search routine. It requires as input a fixed T_{GO} from current time to TPI. Since the AGS cycles in real time with each 2-second guidance step, the TPI search routine advances TPI as current time advances. The pilot may watch the DEDA readouts to determine the time of occurrence of the desired TPI elevation angle.

The TPI direct transfer routine computes the LM state vector at TPI and the CSM state vector at TPF using the Keplerian ellipse predictor. The routine utilizes a Lambert program to solve for the ΔV required for transfer. The iteration in the Lambert program utilizes a convergence tolerance on the transfer time of 2 seconds and has a maximum of eight iterations. Due to computer scaling, all transfer trajectories should have the following properties:

1. Apoapsis height of less than 300 n. mi.

2. Orbital eccentricity less than 0.5.

3. No transfer angle within a 10° band about 0°, 180°, or 360°.

4. No transfer time greater than 2^{13}.

The AGS guidance attempts to orient the X-body axis along the desired thrust direction whenever the RCS or DPS engines are used. If the APS is used, the X-body axis is biased from the desired thrust direction to account for APS engine cant. No correction is made for DPS gimbaling. Active steering ceases, and the system goes to the attitude-hold mode whenever $\overline{V}_G < 15$ fps. Engine shutdown occurs in the AGS whenever the $\overline{V}_G$ component in the X-body axis direction becomes less than 2.1 fps and the $\overline{V}_G$ magnitude is less than 100 fps. A manually controlled RCS burn is not cut off by the automatic logic.

The AGS also has an external ΔV option. The inputs required are

1. Time of the maneuver (ullage on).

2. The target ΔV vector defined in a local horizontal coordinate system defined at the beginning of ullage.

3. Thruster to be used.

The thrust direction is not biased as in the PGNCS.

ANALYSIS OF TEST RESULTS

Tables III, IV, V, and VI are condensations of the results of four test cases devised to discover the relative importance of differences in AGS and PGNCS rendezvous computations. All the tests were based on the E mission "single bubble" rendezvous plan. The tests indicated that most differences in AGS and PGNCS have negligible effects on the trajectory and fuel usage. The following differences had effects noticeable enough to require discussion:

1. The PGNCS coasting integrator has oblateness perturbation terms but the AGS coasting integrator is Keplerian.

2. Due to computer sequencing, during a Lambert burn the PGNCS may use $\overline{V}_G$ values extrapolated over as much as six seconds.

3. The two computers have different cutoff criteria.

4. The PGNCS has no option to allow the astronaut to specify that CDH occurs at a multiple of 180° from CSI.

It is to be noted that the tests were not intended to operationally simulate a mission profile complete with state vector updates; rather, the tests were devised to examine differences in program formulation. Nominal operating procedures will mitigate some of the formulation differences.

Test 1, summarized in table III, is an "end-to-end" simulation of the E mission rendezvous without state vector updates. Trim of residuals was not simulated. This test pointed up the well known fact that without vector updates the error in AGS state vector estimates becomes considerable and causes AGS rendezvous targeting to be in error, which results in considerable TPF miss as compared to PGNCS. In this test case AGS TPF miss was about 40 n. mi. and PGNCS TPF was about 1 n. mi. In this particular test the AGS-targeted CDH maneuver was the prime cause of the TPF miss. Such errors will be negated by the update of the AGS shortly before each maneuver.

The PGNCS estimate of TPI time is quite different from the nominal. That difference can be traced to the fact that the PGNCS CSI ΔV and CDH time are computed based on Keplerian orbit predictions. The result is that the CDH maneuver time is not nominal. TPI time shifts because CDH is not at an apsis as targeted, and the CDH phasing is not as targeted because it was targeted with Keplerian equations.

The PGNCS midcourse maneuver of 2.2 fps in test 1 results from the use of an extrapolated V_G in the targeting of the TPI maneuver.

The difference in cutoff criteria is shown to have a noticeable effect but is not considered significant. The PGNCS cutoff for the 116.7-fps external ΔV "insertion" burn was near perfect. On the same maneuver the AGS underburned by 1 fps. The burn time for the CDH maneuver was less than 6 seconds, and the PGNCS therefore computed T_{GO} only once. Since the programmed constants for the PGNCS short-burn logic are not consistent with the most recent engine data (refs. 7 and 8), the T_{GO} calculation was in error and caused an underburn of about 1 fps. For the CDH maneuver the AGS cutoff criteria also caused approximately 1 fps underburn.

Test 2 consisted of picking off AGS actual state vectors after each maneuver of test 1 and using them in the PGNCS to target the following maneuver in the sequence. The ΔV targeting differences were 2.9 fps for CSI and about 4.5 fps for CDH but become considerable for TPI. The large AGS targeting errors are due to the lack of state vector updates in test 1.

In test 3 both PGNCS and AGS were supplied with nominal pre-maneuver state vectors for each maneuver. Subsequent targeting differences were negligible.

Test 4 was designed to isolate the effect of cutoff differences at TPI. The test setup was devised to cause the AGS and PGNCS Lambert targeting to compute the same TPI maneuver. TPI cutoff effects on mid-course are compared and are small. AGS MCC ΔV was about 0.1 fps and the PGNCS MCC ΔV was about 1.2 fps. The PGNCS MCC ΔV resulted mainly from the use of an extrapolated V_G in the computation of the TPI maneuver.

Another program test was carried out based on the second CSI of the D mission rendezvous. The following list summarizes the test setup:

1. Near circular pre-CSI trajectory.

2. First apsis after CSI is nominally perigee.

3. CDH is scheduled at the first apsis after CSI.

4. Phasing conditions require a retrograde CSI maneuver.

5. The above four items cause CDH to nominally occur 180° from CSI.

Tests made show that a small perturbation to the near-circular, pre-CSI orbit can cause the first apsis after CSI to be an apogee instead of perigee. The phasing conditions still require a retrograde CSI maneuver. But a retrograde CSI maneuver shifts the apogee back very near to CSI. The result of this situation is that the CSI iteration logic is unable to find a solution and exits with an alarm code set. The only 'work-around" available in that situation is to schedule CDH at the second apsis. The resultant position of CDH may then impact the timeline between CDH and TPI. It is recommended that the PGNCS CSI iteration logic be changed as follows:

1. Delete the eccentricity test from the logic for computing CDH time.

2. Place the altitude rate test tolerance of the same logic into erasable memory.

3. Nominally set the value of altitude rate test to 7 fps. These changes will allow another option to handle problems such as the one discussed above. That is, the astronaut is provided with a way of causing the computer to schedule CDH 180° from CSI.

TABLE I.- COMPARISON OF PGNCS AND AGS COMPUTATIONS FOR THE RENDEZVOUS PHASE

PGNCS	AGS
Utilizes both a precision integrator and a two-body integrator for state vector propagation	Uses only two-body motion
Biases the in-plane thrust direction of external ΔV maneuvers (such as CSI and CDH) by one-half the estimated burn arc	Does not bias external ΔV maneuvers (CSI and CDH are not external ΔV maneuvers in the AGS)
Defines the external ΔV thrusting coordinate system to be the local horizontal, local vertical system at the main engine ignition	Defines the external ΔV coordinate system at the start of ullage
Performs the CSI and CDH maneuvers with a fixed inertial thrust direction guidance mode	Redetermines the thrust direction for the CSI and CDH maneuvers each 2-second guidance cycle and is, as such, an "orb rate" guidance mode
Does not redetermine, after execution begins, the CSI or CDH ΔV required	The ΔV required for the CSI and CDH maneuvers is recomputed each 2-second guidance cycle during execution.
Has no constraint on the number of apsidal crossings between CSI and CDH	Has three-apsis crossing capability only
In the pre-CSI routine, has no way to specify CDH time with input other than by apsis crossing number	Has an input option to specify CDH to be positioned at a multiple of 180° from CSI
For either a near-circular orbit after CSI or CSI near an apsis, the program automatically switches from an apsis search to a central angle multiple-of-180°-mode on CDH positioning	Has no such automatic switching

TABLE I.- COMPARISON OF PGNCS AND AGS COMPUTATIONS FOR THE RENDEZVOUS PHASE - Continued

PGNCS	AGS
May target the active vehicle's position at TPI to be in any in-plane quadrant relative to the passive vehicle	May only target the active vehicle to be below and behind or above and ahead at TPI
In the pre-CSI iteration the phase angle computed at TPI is the result of integrating both state vectors to the time of TPI with two-body motion	The CSI iteration assumes near-circular coelliptic orbits and utlizes a first order approximation of true anomaly as a function of mean anomaly in the computation of the TPI phase angle
The program automatically recycles for a new solution if any of the listed targeting constraints are violated or if no solution is obtained in the pre-CSI routine	Makes no checks on constraints. Time between maneuvers, and ΔV values are available to the astronaut through DEDA readouts. The post-CSI periapsis height is not available to the astronaut until after execution.
Has an option to compute the time corresponding to the desired elevation angle	Pilot must determine the TPI time corresponding to the desired elevation angle by watching the DEDA readouts
The midcourse correction maneuver is performed at a programed number of minutes from current time, where current time is the time of program call-up	The midcourse correction maneuver is performed at an input number of minutes from current time
Guidance commands account for DPS gimbaling	Makes no corrections for gimbaling
The local horizontal guidance coordinate system is: X - horizontal, in plane Y - normal to the XZ plane Z - down the radius vector	The local horizontal guidance coordinate system for the LM is: X - horizontal, parallel to the CSM plane Y - normal to the XZ plane Z - down the radius vector

TABLE I.- COMPARISON OF PGNCS AND AGS COMPUTATIONS FOR THE RENDEZVOUS PHASE - Concluded

PGNCS	AGS
Whenever the initial estimate of burn time, T_{GO}, is less than 6 seconds no active steering is performed. During a burn, whenever T_{GO} becomes less than 4 seconds the system is put in an attitude-hold mode.	Whenever $\lvert\overline{V}_G\rvert$ < 15 fps active steering ceases and an attitude-hold mode is activated
The T_{GO} calculations include considerations of engine tail-off. The engine is shut down on a T_{GO} = 0 criterion	AGS does not use T_{GO} as an engine shutdown parameter. Rather, AGS shuts down whenever $\lvert\overline{V}_G\rvert$ < 100 fps <u>and</u> the X-body axis component of $\overline{V}_G$ is less than 2.1 fps.
In Lambert guidance $\overline{V}_G$ is extrapolated by an approximating function over several guidance cycles before being redetermined.	$\overline{V}_G$ is redetermined each guidance cycle of a Lambert maneuver.

TABLE II.- TOLERANCES AND CONSTRAINTS USED IN THE RENDEZVOUS TARGETING PHASE OF THE PGNCS

Tolerance or constraint	Amount
Maximum number of CSI iterations	15
CSI convergence criterion	$\lvert \Delta V \rvert < 0.1$ fps
Circular mode on CDH time is used whenever either	$\begin{cases} e < 0.0001 \\ \dot{R} < 0.05 \text{ fps} \end{cases}$
Minimum time between maneuvers	10 minutes
Minimum periapsis	$\begin{cases} 85 \text{ n. mi., earth} \\ 35\ 000 \text{ ft, moon} \end{cases}$
Bounds on CSI ΔV	$\lvert \Delta V_{CSI} \rvert < 1000$ fps
Maximum number of iterations on the elevation angle	15
Elevation angle search convergence criterion on the phase angle error $\Delta\gamma$	$\lvert \delta\gamma \rvert < 0.1^\circ$
Amount of delay from time of astronaut call-up of the midcourse program until midcourse maneuver execution.	Mission dependent: about 2 - 5 minutes

TABLE III: TEST 1 - PGNCS VERSUS AGS "END-TO-END"

SIMULATION OF E MISSION RENDEZVOUS WITHOUT UPDATES

Maneuver	Parameter	Value	
		PGNCS	AGS
"Insertion"	Burned ΔV, fps	116.7	115.8
	Target ΔV, fps	116.7	116.7
CSI	Burned ΔV, fps	0.25	1.02
	Target ΔV, fps	0.25	1.02
	ΔV_x, fps	0.25	1.02
	ΔV_y, fps	0.0	0.0
	ΔV_z, fps	0.0	0.0
CDH	Time shift from nominal, sec	105	-200
	Burned ΔV, fps	63.9	65.1
	Target ΔV, fps	64.8	66.3
	ΔV_x, fps	61.4	60.9
	ΔV_y, fps	0.0	0.0
	ΔV_z, fps	-21.0	26.0
	Apogee ΔH, n. mi.	-10.0	-9.9
	Perigee ΔH, n. mi.	-9.4	-10.2
	Apsidal skew, deg	2.5	2.3
TPI	Time shift from nominal, sec	156	-33
	Burned ΔV, fps	22.2	22.9
	Target ΔV, fps	22.0	22.6
	ΔV_x, fps	-18.5	-19.4
	ΔV_y, fps	-.3	-.3
	ΔV_z, fps	12.0	11.6

TABLE III: TEST 1 - PGNCS VERSUS AGS "END TO END" SIMULATION

OF E MISSION RENDEZVOUS WITHOUT UPDATES - Concluded

Maneuver	Parameter	Value	
		PGNCS	AGS
MCC	Burned ΔV, fps	2.2	0.09
	Target ΔV, fps	2.2	0.09
	ΔV_x, fps	0.4	0.09
	ΔV_y, fps	0.1	0.0
	ΔV_z, fps	2.2	0.03
TPF	Miss distance		
	x, ft	4.5×10^3	2.1×10^5
	y, ft	2.0×10^3	0.3×10^5
	z, ft	2.9×10^3	1.1×10^5

TABLE IV: TEST 2 - AGS VERSUS PGNCS

UPDATED WITH AGS ACTUAL STATES

Maneuver	Parameter	Value	
		PGNCS	AGS
CSI	ΔV_x, fps	-1.88	1.02
	ΔV_y, fps	0.0	0.0
	ΔV_z, fps	0.0	0.0
CDH	ΔV_x, fps	65.4	60.9
	ΔV_y, fps	0.0	0.0
	ΔV_z, fps	26.2	26.0
	Time shift from nominal for predicted TPI, sec	1489	-33
TPI	ΔV_x, fps	23.0	-19.4
	ΔV_y, fps	-0.4	-0.3
	ΔV_z, fps	32.2	11.6

TABLE V: TEST 3 - PGNCS VERSUS AGS TARGETING

STARTING WITH NOMINAL STATES AT EACH MANEUVER

Maneuver	Parameter	Value	
		PGNCS	AGS
CSI	ΔV_x, fps	-0.21	0.0
	ΔV_y, fps	0.0	0.0
	ΔV_z, fps	0.0	0.0
	Time shift in predicted CDH time from nominal, sec	120	123
CDH	ΔV_x, fps	61.9	61.9
	ΔV_y, fps	0.0	0.0
	ΔV_z, fps	-3.0	-3.0
	Time shift in predicted TPI time from nominal, sec	-84	42
TPI	ΔV_x, fps	-19.6	-19.5
	ΔV_y, fps	-0.4	0.1
	ΔV_z, fps	8.1	7.9

TABLE VI: TEST 4 - EFFECTS OF DIFFERENCES

IN ENGINE CUTOFF

Maneuver	Parameter	Value	
		PGNCS	AGS
TPL	Target ΔV_x, fps	-19.6	-19.6
	ΔV_y, fps	-0.4	-0.4
	ΔV_z, fps	8.1	8.1
	Burned ΔV, fps	21.3	21.38
	V_G Residuals		
	ΔV_x, fps	0.13	-0.05
	ΔV_y, fps	0.09	0.07
	ΔV_z, fps	-0.04	0.0
MCC	Target ΔV_x, fps	0.0	0.11
	ΔV_y, fps	-0.1	0.0
	ΔV_z, fps	1.2	0.09

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